Accelerator Possibilities for Low Energy Antiprotons at the Fermi National Accelerator Laboratory

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Abstract

There is considerable interest in the deceleration of antiprotons for particle physics, atomic physics, gravitational experiments, PET radioisotope production, antiproton capture therapy, and deep-space spacecraft propellant. The only facility in the world presently capable of producing large fluxes of usable antiprotons is the Fermi National Accelerator Laboratory (FNAL). Unfortunately, at this time FNAL has no beamline for extracting decelerated antiprotons to experiments or to portable Penning traps for commercial distribution. In this paper a vision is developed for decelerating antiprotons to progressively lower energies and higher efficiencies.

1 PET Radioisotope Production

The typical positron-emitting isotopes used or desired for medical applications are ^{11}C, ^{13}N, ^{15}O, and ^{18}F. Their half-lives are respectively 20, 10, 2, and 110 minutes. In order to create these isotopes and inject them into the patient before the positron emission is depleted, it has been necessary to have a nearby accelerator for radioisotope generation. In the U.S. there are over 1700 institutions that have PET imaging capabilities, but only 40 isotope-generation clinics exist. Even though the number of disorders being diagnosed by PET is increasing rapidly, the primary obstacle to PET applications is the lack of isotope availability. The problem is that the high cost of cyclotrons restricts the number of PET centers.

This availability problem can potentially be eliminated by a commercial distribution system for antiprotons. Imagine a compact, portable Penning trap which would be brought to any hospital with a PET imaging capability on a regular basis (like deliveries of liquid nitrogen). By spilling antiprotons from the trap into the sample at a kinetic energy of approximately 1 MeV, PET isotopes can be produced in a small, portable, shielded enclosure. It would be possible literally to produce the radioisotopes at the patient's bedside. This makes isotopes such as ^{15}O, which holds so much promise for the diagnosis of brain tumors, viable for use in a hospital environment.

Calculations predict that fewer than 10^{11} antiprotons are required to produce a 15 mCi source for a ^{18}F treatment. In order to verify these calculations, ($\overline{p}$,n) and (*,n) reactions cross section measurements need to be made on carbon, oxygen, nitrogen, and fluorine. A facility for decelerating a small number of antiprotons to 1 MeV kinetic energy would be highly useful for performing these cross section measurements.

2 Antiproton Capture Therapy

An experiment has already been performed on the energy deposition of slow antiprotons in tissue-like material [1]. Comparing with proton deposition, which is quite well understood, one finds a dramatic enhancement of deposited energy with antiprotons at the deposition peak. In this study polythene was used as the tissue-like material. At a depth of 0.5 g/cm^2 the proton and antiproton deposition rates (at 40 MeV kinetic energy) were normalized to unity. As far in as 1.5 g/cm^2, or down to 20 MeV, the proton and antiproton curves are equal. Between 1.5 and 2.0 g/cm^2 the deposition peaks show a dramatic difference. Whereas the proton deposition peak reaches a relative deposition rate of 5, the antiproton peak is as high as 9.

The next round of experiments being proposed is to stack samples of cancer cells into a matrix of tissue-like material and study the effect of antiproton-induced energy deposition on cancer-cell mortality. Ultimately such experiments could lead to patient trials.

3 Interstellar Spacecraft Propellant

In the next 30–50 years NASA has planned a series of unmanned interstellar missions. These missions need a new generation of propulsion systems which can drive these probes out beyond the boundary of our solar system and reach their destinations within 50 years of launch. The most ambitious of these is a mission to the nearest solar system Alpha Centauri, at a distance of 4.6 light-years (10^6 AU). In order to achieve this goal, the probe would have to be accelerated to a peak speed of $0.1c$! Assuming a 1000 kg spacecraft, the kinetic energy of the probe would reach 10^{18} Joules, the energy output of humanity for one day (or 100 Megaton H-Bombs). Closer missions would include studying the Oort cloud (10^4 AU), sending an observatory to the solar gravitational lens focal point (1000 AU), and the hydrogen wall at the bow wake between the solar magnetic field and the interstellar material (100 AU). Remember that the distance from the Earth to the Sun is 1 AU, and a trip to Neptune requires traveling approximately 20 AU.

There are a number of engine designs under active consideration. One is a beamed-energy concept in which a high-power, large-aperture laser is focused onto an immense parachute attached to the probe. Another is a fusion ramjet in which fuel is picked up with a magnetic scoop while the craft is traveling. A third concept is the use of ion engines. By far the most promising ideas require the use of antimatter-matter annihilation.

Now, the matter-antimatter annihilations themselves could not possibly produce sufficient thrust. Instead, think of these annihilations in the same manner that a spark plug is used in a conventional automotive engine. There are many types of engine designs on the drawing board. They range from hybrid fission/fusion concepts with specific impulse, I_{sp}, of roughly 60,000 sec, beam core (I_{sp} of roughly 10^7 sec), solid core (I_{sp} of 800–1000 sec), gas core (I_{sp} of 1000–2500 sec), and plasma core (I_{sp} of 5000–100,000 sec) designs.

As an example, take the strawman AIMStar mission. Assuming an I_{sp} of 61,000 sec, a thrust of 55.2 N, a take-off fuel level of 130 μg of antiprotons, and an engine burn time of 6 months, the mission would require 50 years to reach a distance of 10,000 AU. Many such missions have been recently envisioned [2]. To get an idea of what 130 μg means in terms of number of antiprotons, the conversion factor is that one μg is equal to 6×10^{17} antiprotons. Assuming a future FNAL antiproton production rate of 10^{12} antiprotons per hour, it would require 20,000 years to accumulate this many antiprotons. But given that orders-of-magnitude-higher antiproton accumulation rates can be envisioned, this fuel requirement may not be nearly as crazy at it may seem. In fact, there are preliminary missions to the solar-gravity-lens focal point which would only consume a few years of dedicated FNAL antiproton accumulation.

4 Portable Penning Traps

One of the key technologies required to fulfill the above niches for commercial antimatter distribution is the invention of a portable Penning trap. Two such traps now exist. The later HiPAT trap was built for the NASA Marshall Space Flight Center (MSFC) by Synergistic Technologies, Inc. through a Small Business Innovative Research (SBIR) grant.

To this date the HiPAT trap has been tested with protons. The protons are generated by ionizing residual hydrogen molecules in the trap volume with a 3 keV electron beam. These tests are taking place at the NASA MSFC Propulsion Research Center. The HiPAT trap was designed to store 10^{12} antiproton in a 4 Tesla magnetic field bounded by a 20 kV potential well. Due to the fact that the solenoid is superconducting, the trap walls are acting as a cryopump, reducing the pressure in the volume to 10^{-12} Torr. At this pressure, a 400-day antiproton lifetime is anticipated.

5 Antiproton Availability at Fermilab

The anticipated antiproton production "stacking" rate for the next Tevatron Collider run (Run IIa) is 2×10^{11} antiprotons/hour. Realistically, a rate half that value is probable during 2001. It is anticipated that a typical Tevatron Collider store will last 6–7 hours. Therefore, given that it takes 1–2 hours to refill the Tevatron, there should be on average three transfers per day. Given a maximum consumption rate of 10% of the overall stacking rate, the flux of antiprotons for low-energy applications could reach the level of 3 transfers per day at approximately 10^{11} antiprotons per transfer.

In 1996 there were a number of proposals for further increases in the antiproton stacking rate at Fermilab. Under the umbrella of the Tevatron33 project, these upgrades were designed to attain a stacking rate of 10^{12} antiprotons/hour. Due to limited resources, personnel, and time these upgrades have not been seriously studied further since that time. There will surely be work on these upgrades in proton intensity and efficiency of antiproton capture and cooling once Run IIa is well underway later in 2001 or early 2002.

If one is not interested in generating an antiproton beam for the Tevatron Collider, but lower-energy antiprotons for the above applications or low-energy particle physics, the traditional methods for creating, capturing, and cooling antiprotons may no longer be optimal. In fact, recently some novel accelerator configurations have been proposed which have the potential of increasing the antiproton stacking rate by two or three orders of magnitude. Such large increases would make it possible to fulfill even the demands of the more ambitious NASA interstellar missions, or provide PET diagnostic treatments which would meet much of the anticipated demand.

6 Overview of FNAL Options

The options described in this section have been considered in the past or are currently the focus of ongoing accelerator research and development. The list is ordered chronologically.

A. Deceleration in the Accumulator Ring

This is the present means by which antiprotons are decelerated at FNAL. Because the Accumulator [3] has a peak momentum of 8889 MeV/c, in principle it should be able to decelerate antiprotons down to 500 MeV/c. In addition, it already has cooling systems built into it.

Unfortunately, there are two problems with regularly decelerating antiprotons in the Accumulator during Tevatron Collider operations. First, deceleration in the Accumulator is slow and very staff intensive. Second, it is completely destructive to any remaining antiprotons and therefore highly disruptive to normal collider operations.

B. Deceleration in the Booster Ring and Linac

This was the original scheme for decelerating antiprotons which was proposed in 1993. It has many technical problems, such as the fact that the Booster RF cavity bias power supplies do not source reverse current, and hence the cavities do not track the beam frequency during deceleration. In addition, the antiproton extraction optics would have to be fit into a machine lattice that is already quite full. As usual the Devil is in the details!

C. Decelerate in the Booster Ring and the IUCF Cooler

The Booster (with the modifications mentioned above) is capable of decelerating an antiproton beam to a kinetic energy of 400 MeV. A better and more efficient method for further deceleration is to copy (or borrow) the IUCF cooler ring, which has a peak energy very close to 400 MeV. At present there is a proposal to have the IUCF staff study deceleration in their ring using protons, to understand the efficiencies of electron and stochastic cooling, and to understand the issue of space charge dominated beam storage.

D. Deceleration in the Main Injector to 2 GeV/c

This is an active program at FNAL. The idea is to use the outstanding magnetic field quality of the new Main Injector dipole magnets to decelerate the antiprotons to 2 GeV/c, which is thought to be the lowest momentum that antiprotons can be brought down to with full efficiency. Further deceleration in a low energy ring would then take place to a momentum of 100 MeV/c (a kinetic energy of 5.3 MeV).

The magnet power supplies and RF control system have already been shown to track the entire deceleration ramp. More recently, protons have been decelerated to 3 GeV/c. Further deceleration experiments will take place once software has been written which improves beam control at the lower momenta.

Perhaps the best selling point of the Main Injector deceleration approach is the fact that it can be implemented adiabatically at low incremental costs. As more of the plan is experimentally confirmed, further accelerator improvements and extensions can be implemented with lower technical risk.

The following sections describe in more detail each of the near-term adiabatic steps being contemplated at FNAL.

i. Decelerate protons in the Main Injector

The goal of this step is to attain a proton momentum of 2 GeV/c. This activity will continue through the Summer of 2001, with continuously upgraded instrumentation and RF capabilities being installed in order to improve the deceleration efficiency.

The RF issues are the most pressing, with cavity tuning being dominant. Because of the 10% change in RF frequency during deceleration, the RF cavity resonant frequency cannot track all the way down to 2 GeV/c. This results in a limit to the amount of RF voltage available during deceleration, which in turn slows down the ramp and limits the amount of beam which can be decelerated. At present the deceleration ramp requires 20 seconds, which is roughly 10 times longer than a normal Main Injector ramp. A number of solutions have been proposed. It will soon be necessary to choose one such solution and develop it.

In addition, because the loss of antiprotons in a degrader is so significant, there is great interest in decelerating beam in the Main Injector even lower, perhaps as low as 1 GeV/c or even 500 MeV/c. It is known that beam loss would occur due to the limited transverse aperture of the Main Injector. On the other hand, the estimated 30-50% deceleration efficiency would be more than compensated by the order of magnitude increase in antiproton transmission through the shorter degrader material.

Figure 1 shows a picture of the Southwest corner of the FNAL site on which the Main Injector is indicated. Note that the extraction point for the antiprotons is also designated.

Figure 1: Photograph of the Southwest corner of the FNAL site. Indicated on the picture are the Tevatron Collider, the Main Injector, and the antiproton extraction point from the Main Injector.

ii. Extract decelerated antiprotons

Once the antiprotons are decelerated, it is necessary to extract them out of the Main Injector into a beamline. The reality of the Main Injector is that there is not much space to add kicker magnets and Lambertson magnets, which are necessary for efficient extraction of beam from a circular accelerator. Fortunately, there is a very elegant solution.

Antiprotons and protons circulate in a magnetic accelerator lattice in opposite directions along exactly the same path. Therefore, to extract antiprotons one merely needs to use a proton injection Lambertson and kicker. These elements exist at MI-10 where the proton beam from the FNAL Booster is injected into the Main Injector. Figure 2 shows a picture of the area in the Main Injector tunnel where antiproton extraction is planned to take place. Note that the area is quite empty, a condition that will still be true after the MiniBoone transfer line is installed in the space occupied by Cons Gattuso in the picture.

iii. Antiproton transfer line construction

Once extraction of antiprotons is accomplished, delivery of this beam to an experimental area is desired. This is the goal of this stage. As shown in Figure 3, the experimental area is built just outside of the Main Injector tunnel between the service buildings MI-8 and MI-10. This experimental area is linked to the Main

Figure 2: Photograph of the area in the accelerator tunnel where the proton injection line meets the Main Injector. This is the location where the 2 GeV/c antiproton extraction transfer line will be installed.

Injector tunnel by a 2-ft diameter steel pipe within which the transfer line and electric conduits are routed. Figure 4 shows a close-up sketch of the geometry of the experimental area. Of course the great problem in this configuration is the excessive beam loss which occurs in the degrader.

It is anticipated that the steel pipe will be pushed in January of 2001, and antiproton transfers into the experimental enclosure for use by experimenters will commence in the Summer of 2001.

iv. Antiproton deceleration ring construction

While experiments are underway in the degraded beam experimental area, the plan is to construct and commission the antiproton deceleration ring shown schematically in Figure 5. The peak momentum of the ring is nominally 2 GeV/c, though it may be slightly increased if there is a particle physics niche that could be reached by this increase.

The ring has a primary and secondary mission. The primary mission is to decelerate antiprotons down to 100 MeV/c. At this momentum the antiprotons can be extracted into an RFQ for further deceleration and capture in a Penning trap. It is very likely that cooling is not required in this ring for this mission.

The secondary mission is to support particle physics experiments. The two likely experimental configurations are fixed target via internal gas jet and proton-antiproton collisions. In both these cases electron cooling would be a very powerful tool for maintaining and improving the luminosity in the experiments, far superior to stochastic cooling [3] used in the FNAL Accumulator ring.

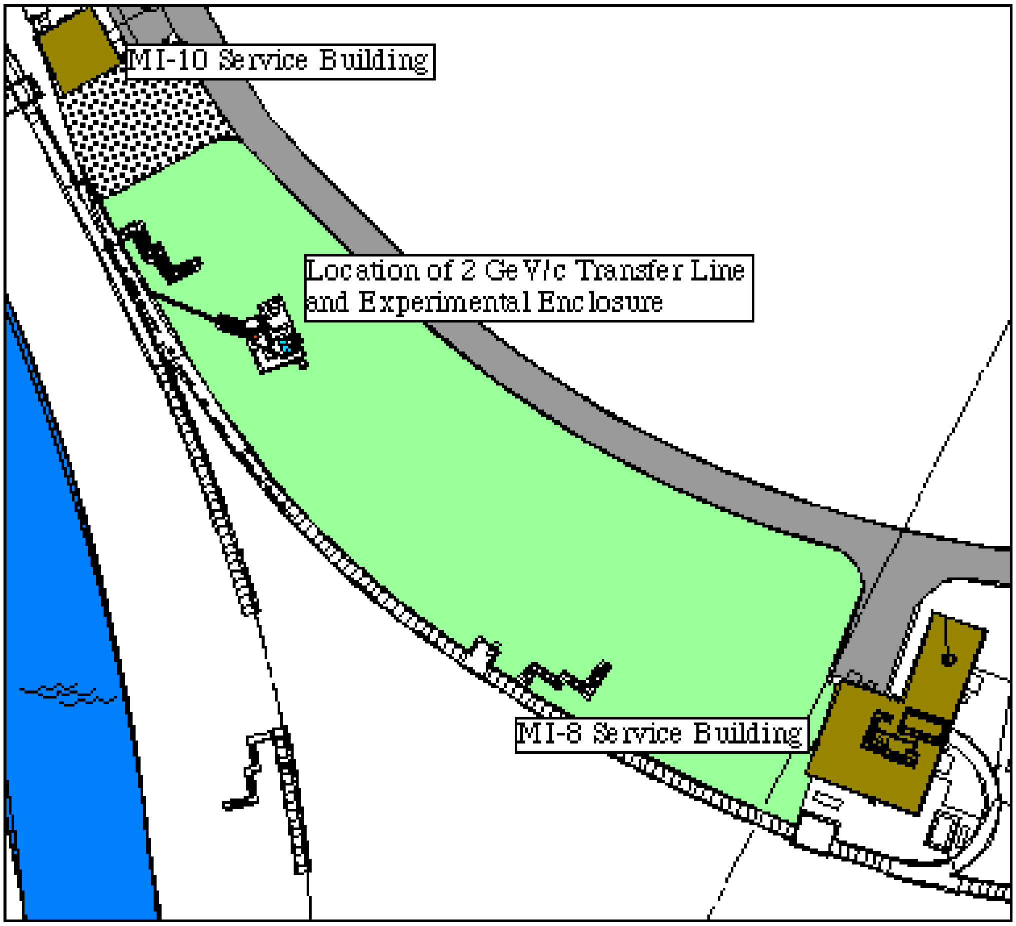

Figure 3: Sketch of the geometry of the 2 GeV/c antiproton transfer line and the location of the experimental station in which the antiprotons are further decelerated via dE/dx in a degrader.

The goal of this step is to design the ring during calendar 2001 and perform the construction in 2002. After a few months of commissioning, it is probably that both the primary and secondary missions of this ring could be started in the Summer of 2003. Any existing collaborations who are potentially interested in performing an experiment in this ring should contact the author and start putting together detector geometries and beam requirements very soon.

E. New facility with far greater stacking rates

This is a very new development which was motivated by interest and financial support provided by Technanogy, LLC [4]. The goal of this facility is to increase the antiproton production rate by 2 or 3 orders of magnitude. Preliminary design work is already underway, with more intense efforts beginning in the Spring of 2001.

It is likely that the this facility will utilize a new target geometry and entirely new accelerator facility downstream of the Main Injector. One probably location for this facility is to the south of the Main Injector and Tevatron in the fields at the bottom

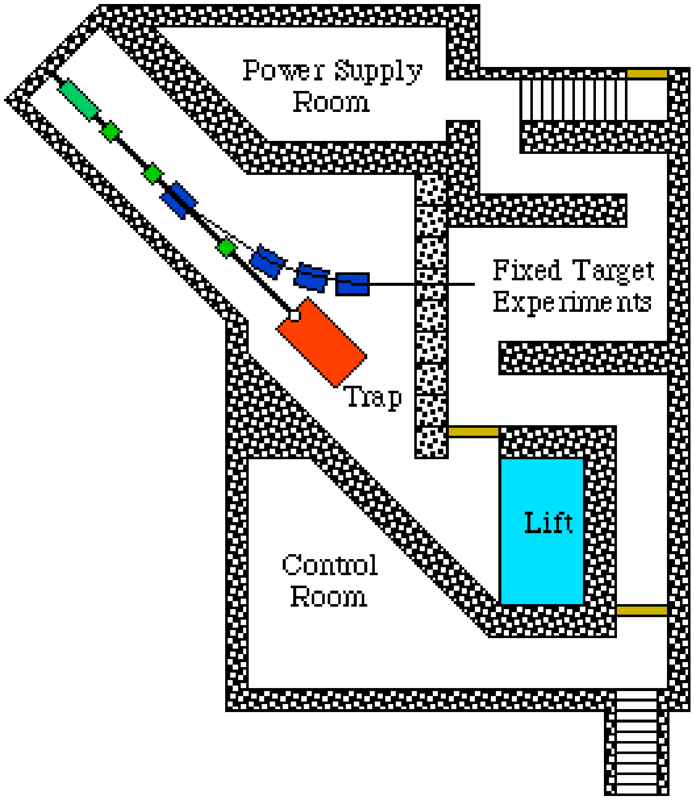

Figure 4: Sketch of the experimental enclosure in which antiprotons are further decelerated via dE/dx in a degrader. Indicated on the sketch are the Penning trap and a separate experimental area for patient therapy tests and other fixed target studies.

of the picture in Figure 1.

7 Conclusions

A staged plan has been proposed in which each intermediate step represents an adiabatic expansion of capabilities for modest cost and effort. The motivation for this work is not particle physics, but instead commercial interest in distributing antiprotons for medical and space propulsion applications. Nonetheless, particle physics experiments are welcome and encouraged.

The first step is to decelerate protons to 2 GeV/c in the Main Injector. There is every reason to believe that the Main Injector is already capable of decelerating with only very modest hardware modifications and some significant software extensions. In fact, deceleration to 3 GeV/c with protons has already been achieved. Subsequent steps lead in the short term to a dedicated antiproton deceleration ring operational in 2003. In the farther future a new facility capable of increasing the antiproton production rate by two or three orders of magnitude is under consideration.

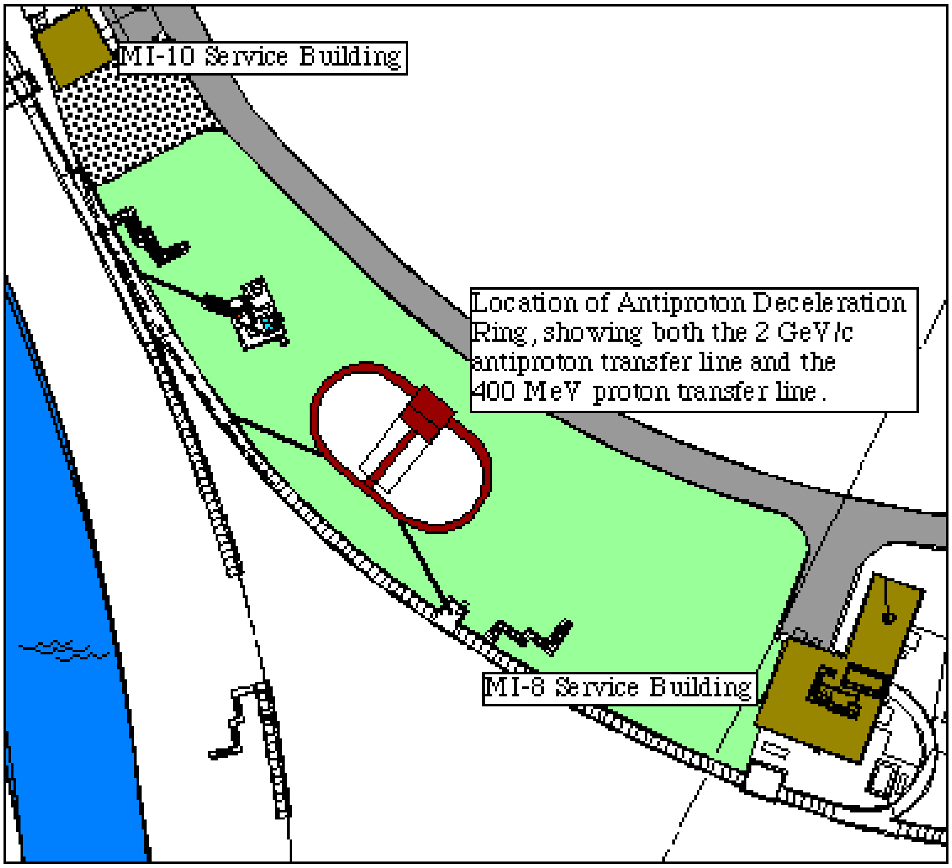

Figure 5: Sketch of the geometry of the antiproton deceleration ring, also showing its antiproton 2 GeV/c transfer line and 400 MeV kinetic energy proton transfer line. The protons are used to commission the ring and allow collider-mode particle physics experiments.

8 Acknowledgements

In this paper I have drawn the medical and space propulsion applications background from talks given by Steven Howe of LANL/Synergistic Technologies and Gerald Smith of Penn State University/Synergistic Technologies.

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